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Automating the Identification of Worst-case Design Scenarios

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"You are here"

- This is the last in a series of papers introducing advanced methods for design automation
  - Parametric Modeling:
    - SAE 981574, ICES, July 1998
  - Design Optimization:
    - "Nonlinear Programming Applied to Thermal and Fluid Design Optimization," ECTC/ITHERM, May 2002.
  - Automated Correlation ("Calibration"):
    - "Nonlinear Programming Applied to Calibrating Thermal and Fluid Models to Test Data," SEMI-THERM, March 2002.
  - Multidisciplinary Analysis and Optimization (MDO/MDA):
    - "Integrated Analysis of Thermal/Structural/Optical Systems," and "Automated Multidisciplinary Optimization of a Space-based Telescope," SAE 2002-01-2444 and 2002-01-2445, July 2002.
  - **Automated Worst-Case Scenario Seeking**

Worst-case Design Scenarios

- The first step in a design process is to identify the worst-case scenarios.
  - The design will be developed and tested against these scenarios: their revision often forces a design change.
  - For thermal engineers: one “hot case” and one “cold case” as a minimum
- Margins and uncertainties are stacked up
  - Conditions that can’t possible happen or co-exist (e.g, BOL properties combined with EOL dissipations, or steady-state at the subsolar point or within a planetary shadow)
- In spacecraft systems, it is often not clear what stack-up or combinations yield the worst case, especially with articulating components and complex dissipations

The Problem

- Despite the criticality of the results, cost of searching for the worst case scenarios can be prohibitive
  - The number of cases grows geometrically
  - Most older software does not facilitate repeated runs nor take advantage of previous solutions
  - In complex missions, the search must be repeated many times during design development
- Approaches are informal (since no standards exist) and rarely efficient. Common approaches:
  - Full factorial (FF) search (all possible combinations of discretized uncertainties)
  - Monte Carlo (MC) search (hundreds to thousands of randomized samples: a “shotgun” approach)

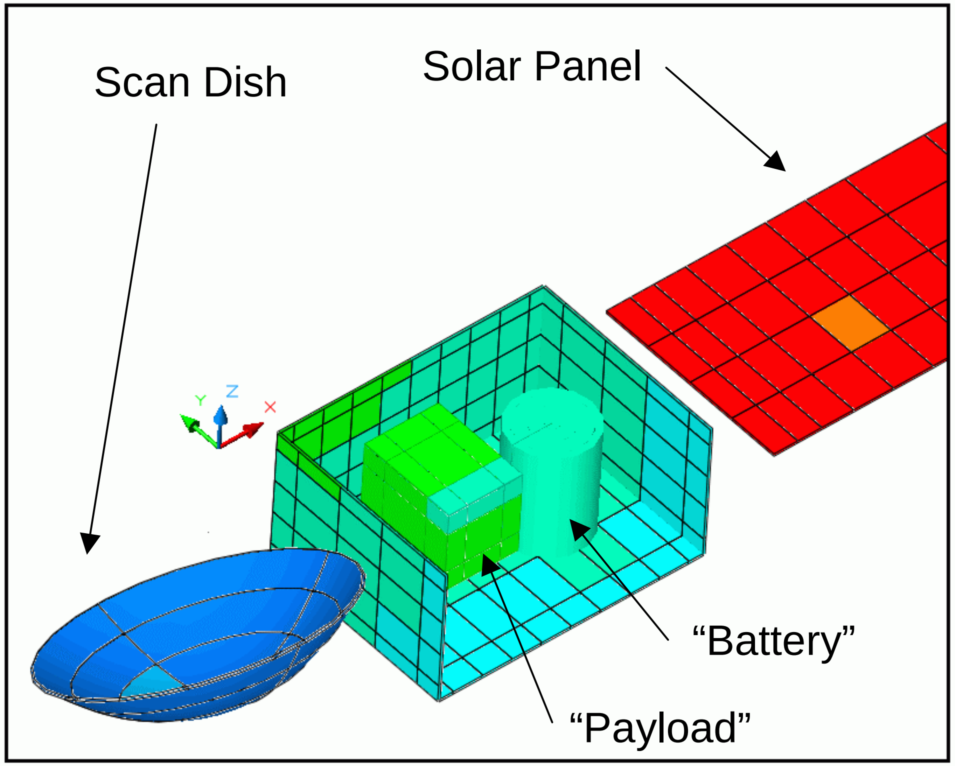
New Technology

- Parametric Software
  - Repeated runs can be scripted and searches automated
  - Special effort spent minimizing recalculation costs
- Latin Hypercube (LH) Scan
  - Requires fewer samples than full factorial or Monte Carlo
- NLP (Gradient-based Optimization) Search
  - Directly seeks *the* worst case with minimum evaluations
- Hybrid LH/NLP Method
- Future: Elimination of search-then-design; the elimination of worst-case scenarios altogether

Demonstration Problem

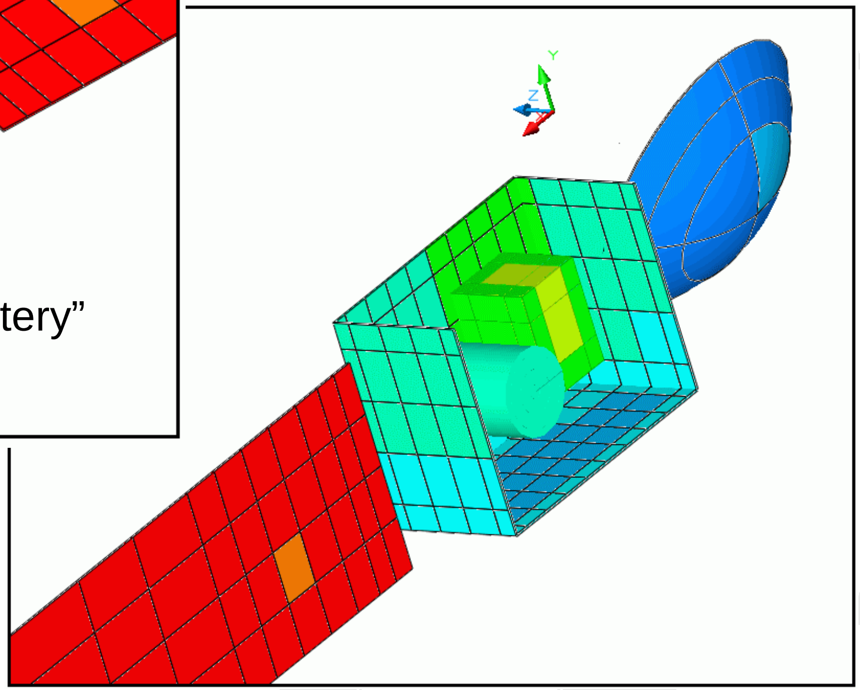
- Simple Sample Problem:
  - 3-axis stabilized LEO (300km) nadir-facing box
  - 2-axis tracking solar panel on leading side (+X)
  - 1-axis scanning (+/- 30°) paraboloid dish on trailing side (-X)
  - 60W "payload" with 600W 10 minute pulse on the +Z face
  - SPV/CPV "battery" on the -Z face, realistic charge/discharge/trickle-charge profiles vs. shadow
  - +Y and -Y faces are fully utilized as radiators
  - Thermal Desktop® model available upon request
- What is the hot case beta angle, dish position, and start time for the power pulse?

Sample Problem Definition



+Z and -Y faces removed

-Z and +Y faces removed



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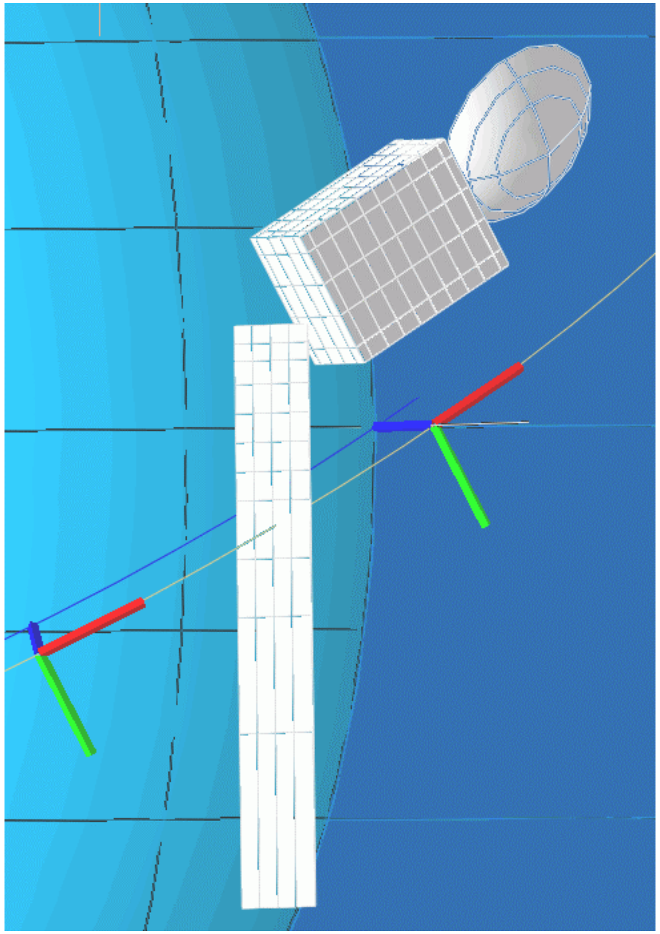
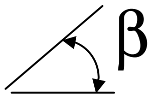
Sample Problem Definition



Shadow exit at $\beta = 30°$



Unknowns:

1. Beta Angle (0 to 90)
2. Dish Scan Angle (-30 to 30)
3. Pulse power timing (0 to 5400s)

Tools Used

- Thermal Desktop/RadCAD® for thermal/radiation model
  - 15 orbit points, steady state plus 2 transient orbits per evaluation for cyclic convergence
- Thermal Desktop® "Dynamic Mode:" SINDA/FLUINT commands changes and recalculations as geometry/orbits change
  - per SINDA/FLUINT statistical analysis and optimization routines
- Total time to evaluate one case (all radiation and conduction recalculations, steady/transient simulations): 45 seconds on a 1.8GHz Pentium® 4.

Full Factorial Scan

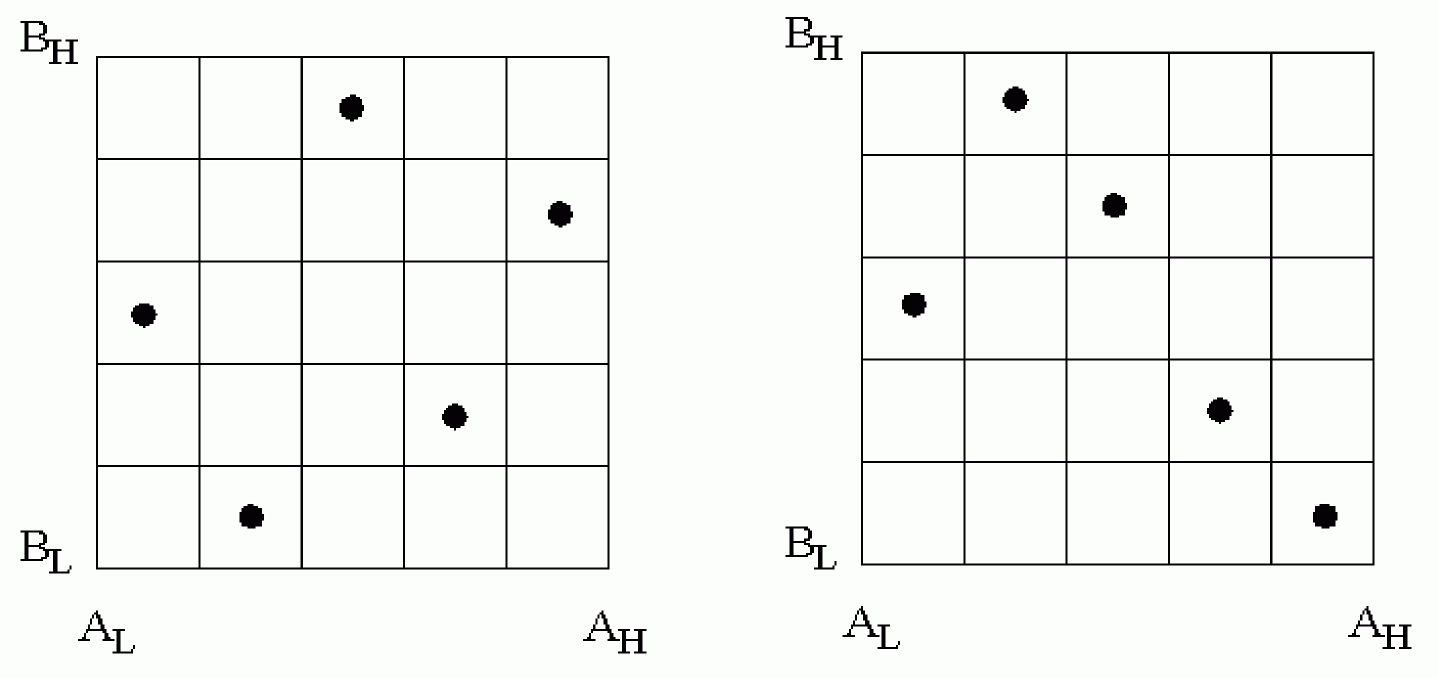
(4x3x4=48 evaluations)

- 4 beta angles: 0, 30, 60, 90
- 3 scan angles: -30, 0, 30
- 4 pulse start times: 0, 1600, 3200, 4800 sec. from subsolar point

Component	beta angle (deg)	scan angle (deg)	pulse start time (sec)	Peak Temp (K)	Time of Peak (sec)
Battery	60	-30	0	291.7	3525
Payload	90	-30	0	301.8	760

Latin Hypercube Explained

- For N samples made, each parameter uniquely sampled 1/N times
- For 2 variables A and B, if N=5:



Latin Hypercube Results

- N=20 Samples (usually <20% of FF method)
  - Example: β = 2.25, 6.75, 11.25, ... 87.75
- Found hotter temperatures in less evaluations:

Component	beta angle (deg)	scan angle (deg)	pulse start time (sec)	Peak Temp (K)	Time of Peak (sec)
Battery	47.25	-1.5	1088	291.8	3683
Payload	78.75	13.5	122	303.0	880

Nonlinear Programming (Optimization) Approach

- Instead of “What is the best design” ask “What is the worst case?”
  - Best design: vary A, B, C to minimize cost
  - Worst case: what combination of A, B and C yield the maximum temperature (hot case)?
- Good news: finds the worst point, not just nearby point
- Bad news: sensitive to initial conditions
  - Number of evaluations unknown (usually 20 to 100)
  - Requires one search *per component*
  - Might ‘stall’ at a local minimum
    - This isn’t serious for design optimization, but is more troublesome for test data calibration and is *acute for worst-case seeking*

Hybrid Method

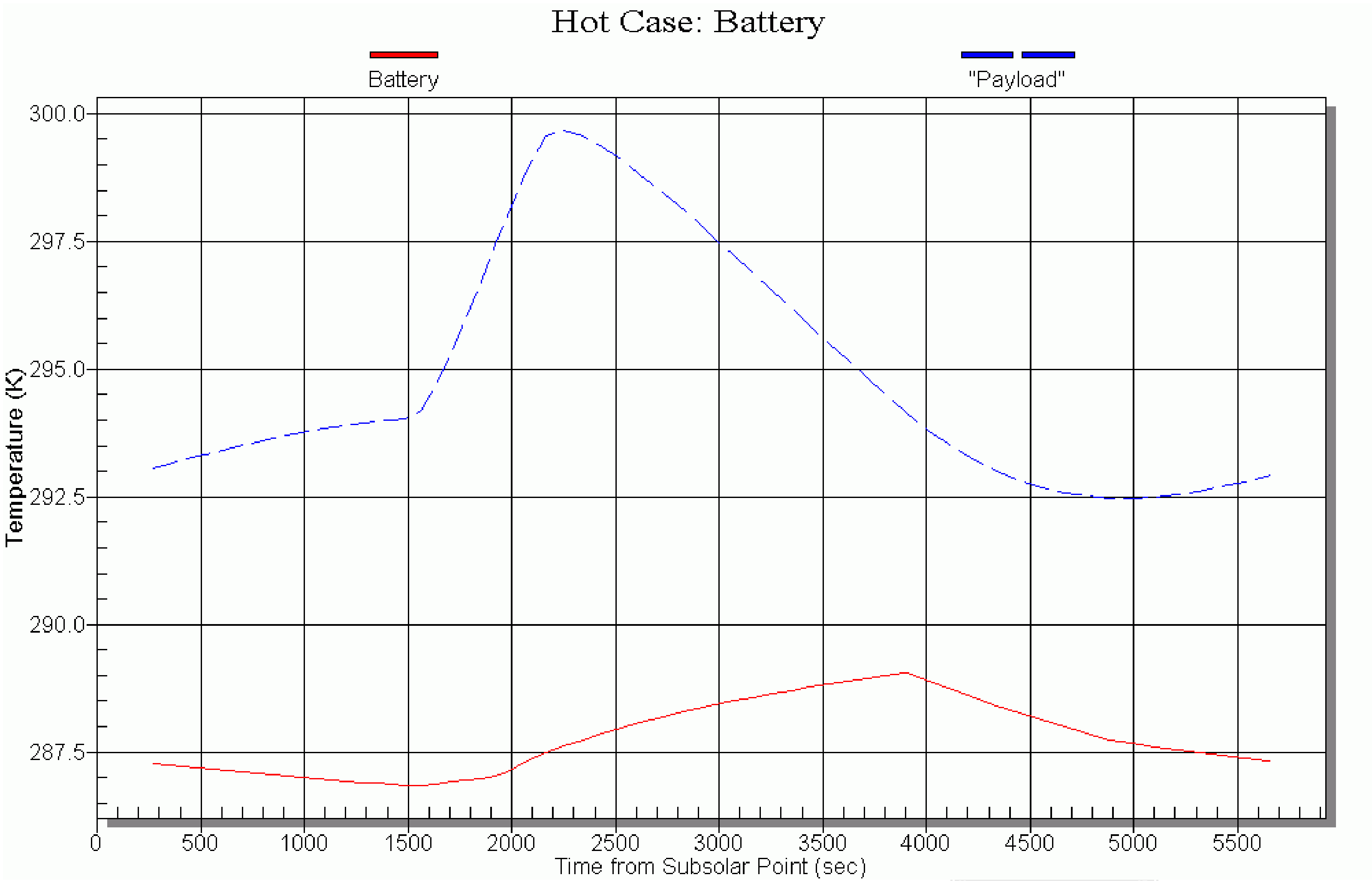
- Find good starting point with quick (say N=10) LH scan
- Finish off with NLP (optimization)
- Overcomes both initialization sensitivity of NLP and discretization limitation of LH. The cost of LH "prescan" usually pays for itself in reduced NLP evaluations

Component	beta angle (deg)	scan angle (deg)	pulse start time (sec)	Peak Temp (K)	Time of Peak (sec)
Battery	47.9	0.8	1276	292.1	3678
Payload	73.5	17.3	7.1	303.7	774

Results Discussion: Sample Model

- Results
  - Battery peaked at intermediate beta angle: too low and the -Z face doesn't get much sun, too high and the battery isn't used
  - Payload peaked at fuller sun (high beta, but less than 90!) and when pulse began near the subsolar point
- In retrospect:
  - Beta angle was the most important
  - Pulse start time was of intermediate importance
  - Scan angle for the dish was not important
- FF and MC waste time resolving unimportant parameters. Discrete sampling like LH preserves resolution of important parameters.

Battery's Hot Case



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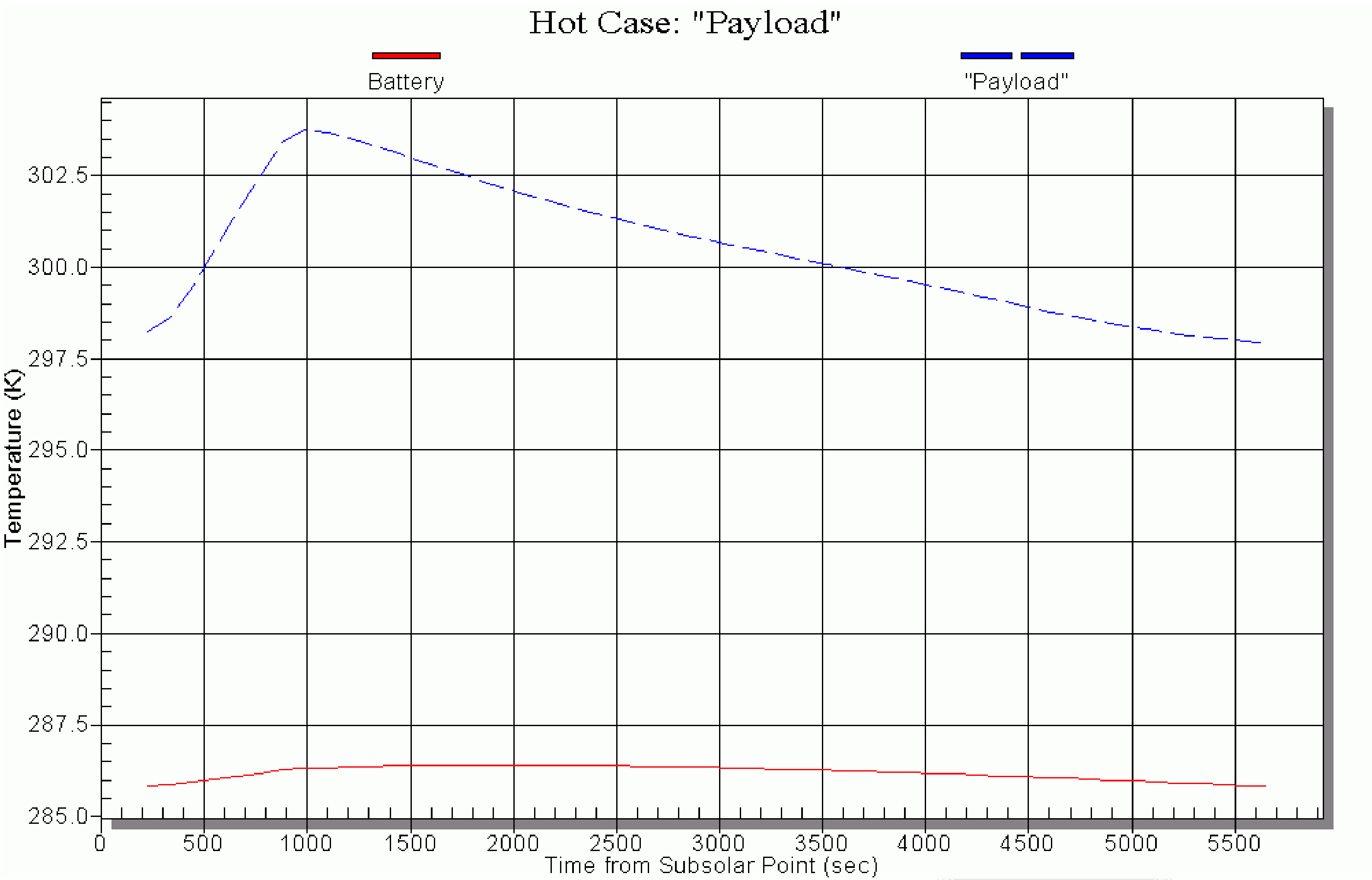
Payload's Hot Case



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Conclusions

- Existing statistical analysis and optimization tools can significantly reduce the cost (and improve the accuracy) of worst-case searches
- Just like model calibration to test data, another nasty task has been automated

Even More Advanced Techniques

- Near Term (tomorrow if needed)
  - Response Surface Models (RSM)
    - Inject after the LH scan and before the NLP search to tremendously speed the latter
  - Sampling based on actual probability of occurrences rather than uniform distribution functions
    - Example: sinusoidal scan angle
- Far Term (the ideal, even if not currently achievable)
  - Dispense with a separate worst-case search
    - Reliability-based optimization and robust design techniques
    - Instead of a scenario-then-design-then-check, incorporate probabilistic scenarios into automated design production